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Crankshaft Major Change Certification Using Improved Fatigue Testing Methods

May 25, 2006

2006 Designee Conference
Rotorcraft Directorate

"In general, limitations in properties of existing materials are major factors limiting our ability to meet such modern needs as more efficient power sources."

Preface
Structure and Properties of Engineering Materials
Brick, Pense, and Gordon

".... A "minor change" is one that has no appreciable effect on the weight, balance, structural strength, reliability, operational characteristics, or other characteristics affecting the airworthiness of the product. ***All other changes are "major changes" .*** *...."*

14CFR Part 21
§21.93(a), "Classification of changes in type design"

Crankshaft Major Change Certification Using Improved Fatigue Testing Methods

- Background
- Current Regulations / Guidance
  - 14CFR Part 33
  - Advisory Circular 33.19-1
- Certification Test Plan Development
  - Need for Improved Approach to Fatigue Testing
  - Demonstration of Defined Factor of Safety
  - Use of Analytical Tools (FEA)
- Results

Crankshaft Major Change - Material

<u>Traditional Alloy = AISI 4340 VAR</u>

- Implemented as Improvement for Wear/Fatigue
- "Specialty Steel" – Expensive, Long Lead Time
- Difficult to Nitride
  - Temperature near minimum tempering temperature
    - Consequence of Deviation High
  - Sustain for long time period
- Potential Safety Risk
  - Limited Availability
  - Long Lead Time
  - Process difficulty
- ***<u>Consequences of Crankshaft Failure are High</u>***

Crankshaft Major Change - Material

Alternative Alloy = Proprietary Superior Specification

- Improved Nitriding Capability
  - Alloy Chemistry – Nickel and Chrome
  - Lower Nitriding Temperature
    - Greater Process Safety Factor
  - Shorter Nitriding Cycle Time

- Better Commercial Availability

- Benefit to Reciprocating Aircraft Engine Applications
  - Improved Process Safety Factor
  - Improved Manufacturing Availability

- ***Demonstration of Long Term Durability Essential Prior to Implementation***

Regulations and Guidance

14CFR Part 33, “Airworthiness Standards: Aircraft Engines”

– § 33.19, “Durability”

a) Engine design and construction must ***minimize the development of an unsafe condition*** of the engine ***between overhaul periods***…….

FAA Advisory Circular 33.19-1, “Guidance Material for 14 CFR §33.19, Durability, For Reciprocating Engine Redesigned Parts”

Type 1 Components: Forced Vibratory Response

➢ **Type 2 Components: Forced Vibratory Response + Resonant Vibratory Response**

Type 3 Components: Forced Vibratory Response + High Structural Temperatures

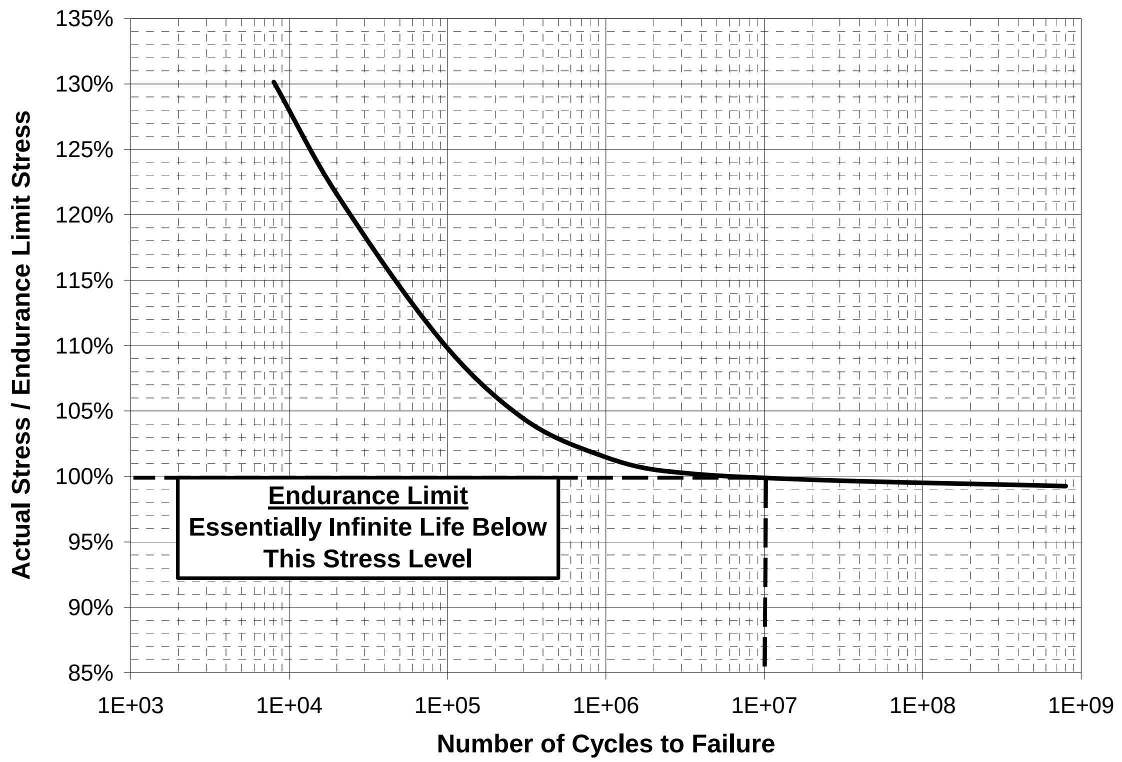
Type 2 Tests:

- Vibration test per 14CFR Part 33 §33.43
- 150-Hour test per 14CFR Part 33 §33.49
- Unique Durability Test
  a) 100 hours at take-off power
  b) 50 hours cruise power

Regulations and Guidance

Evaluation Basis – Demonstrated Fatigue Durability

- “Asymptotic” fatigue curve
- Endurance Limit at 10 million cycles
- bending and torsion



Regulations and Guidance

14CFR Part 33, "Airworthiness Standards: Aircraft Engines"

– § 33.43, "Vibration Test"

a) Each engine must undergo a ***vibration survey*** to establish the torsional and bending vibration characteristics of the crankshaft …… over the range of crankshaft speed and engine power, under steady state and transient conditions, ***from idling speed to either 110 percent*** of the desired maximum continuous speed rating or 103 percent of the maximum desired takeoff speed rating, whichever is higher…….

b) The ***torsional and bending vibration stresses of the crankshaft*** ……. ***may not exceed the endurance limit stress of the material*** from which the shaft is made……. the engine must be run at the condition producing the ***peak amplitude until, for steel shafts, 10 million stress reversals*** have been sustained without fatigue failure …..

c) Each accessory drive and mounting attachment must be loaded……..

d) The vibration survey described in paragraph (a) of this section must be repeated with that cylinder not firing which has the most adverse vibration effect….. and compliance with paragraph (b) of this section need not be shown

Demonstrated Durability:

- ***10 million cycles at worst case condition***
- ***bending and torsion***

Regulations and Guidance

14CFR Part 33, "Airworthiness Standards: Aircraft Engines"

– § 33.49, "Endurance Test"

a) Each engine must be subjected to an endurance test that includes a ***total of 150 hours of operation*** (except as provided in paragraph (e)(1)(iii) of this section) and, depending upon the type and contemplated use of the engine, consists of one of the series of runs specified in paragraphs (b) through (e) of this section, as applicable…..

b) *Unsupercharged engines and engines incorporating a gear-driven single-speed supercharger.*

c) *Engines incorporating a gear-driven two-speed supercharger.*

d) *Helicopter engines*

Regulations and Guidance

14CFR Part 33, “Airworthiness Standards: Aircraft Engines”

– § 33.49, “Endurance Test”

33.49(b), Unsupercharged engines.....

Hours	Speed (2700 RPM – Max Rating)	%Max Rated BMEP	Bending Stress Cycles *
100	2700	100.0	8.10×10^6
25	2500	86.4	1.88×10^6
5	2457	82.4	0.37×10^6
5	2403	78.6	0.36×10^6
5	2349	74.7	0.35×10^6
5	2282	70.9	0.34×10^6
5	2147	62.8	0.32×10^6
150			11.72×10^6

Based upon maximum rated power.

* Bending Stress Cycles = Hours * RPM *60 Min/Hr * 1 Bending Cycle/2 Crankshaft Rev

= 1 Stress Reversal through 1 Power Cycle

Regulations and Guidance

FAA Advisory Circular 33.19-1, “Guidance Material for 14 CFR §33.19, Durability, For Reciprocating Engine Redesigned Parts”

Type 2 “Unique Durability Test”

Hours	Speed (2700 RPM – Max Rating)	%Max Rated BMEP	Bending Stress Cycles *
100	2700	100.0	8.10×10^6
50	2500	86.4	3.75×10^6
150			11.85×10^6

Based upon maximum rated power.

* Bending Stress Cycles = Hours * RPM *60 Min/Hr * 1 Bending Cycle/2 Crankshaft Rev

= 1 Stress Reversal through 1 Power Cycle

Regulations and Guidance

AC 33.19-1 Test Requirements -

33.49(b), Endurance, Unsupercharged engines.....

Hours	Speed (2700 RPM – Max Rating)	%Max Rated BMEP	Bending Stress Cycles	Torsional Stress Cycles
100	2700	100.0	8.10×10^6	
25	2500	86.4	1.88×10^6	
5	2457	82.4	0.37×10^6	
5	2403	78.6	0.36×10^6	
5	2349	74.7	0.35×10^6	
5	2282	70.9	0.34×10^6	
5	2147	62.8	0.32×10^6	

33.43(b), Vibration Durability

28 *	2970 *	100.0 *	2.49×10^6	10.0×10^6

Unique Durability Test

100	2700	100.0	8.10×10^6	
50	2500	86.4	3.75×10^6	
328			26.06×10^6 **	10.0×10^6

* Based upon torsional survey results

*** 7.37×10^6 cycles (28.2%) at partial power*

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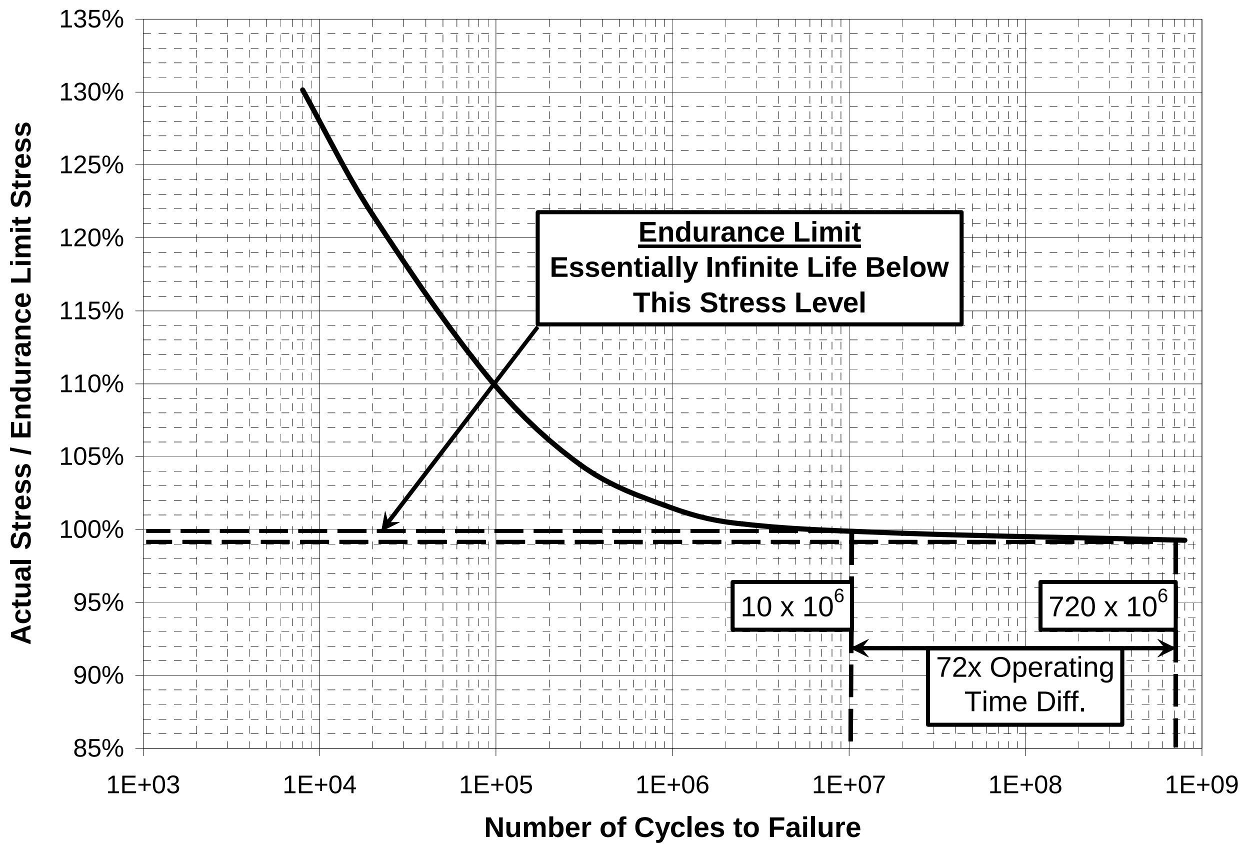
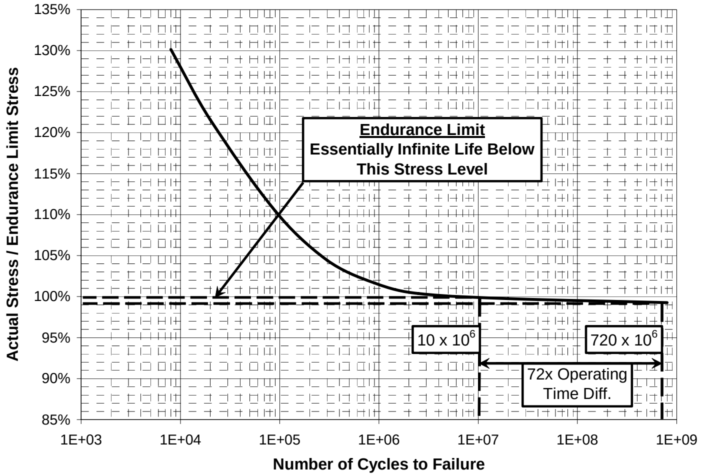
Concerns

- Does not demonstrate long term fatigue durability
  - S-n Curve varies with material / alloy used
  - Unanticipated duty cycles / relation to 10^7 cycle endurance limit



Concerns

- No Significant Factor of Safety Demonstration
  - Success in terms of Maximum Rated Loads Only
  - Inadvertent manufacturing deviations
  - Unanticipated operating conditions
  - Minimum benefit from extension of test length



"The fatigue of materials has been the subject of extensive research and publication for many years. …Its basic physical and chemical causes are still not completely understood."

The Internal-Combustion Engine in Theory and Practice

Charles Fayette Taylor

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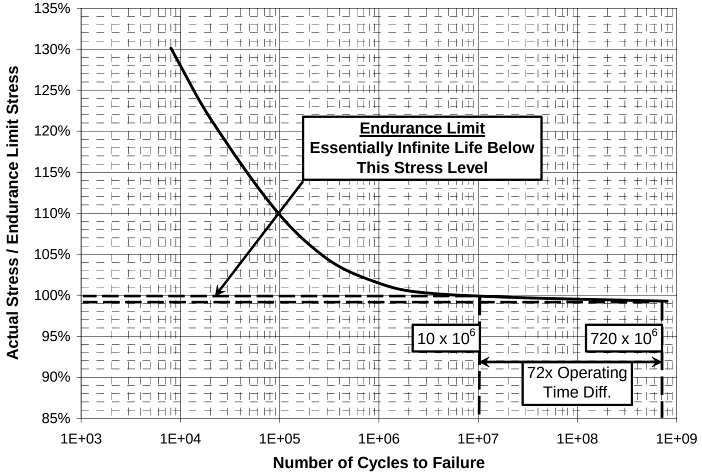
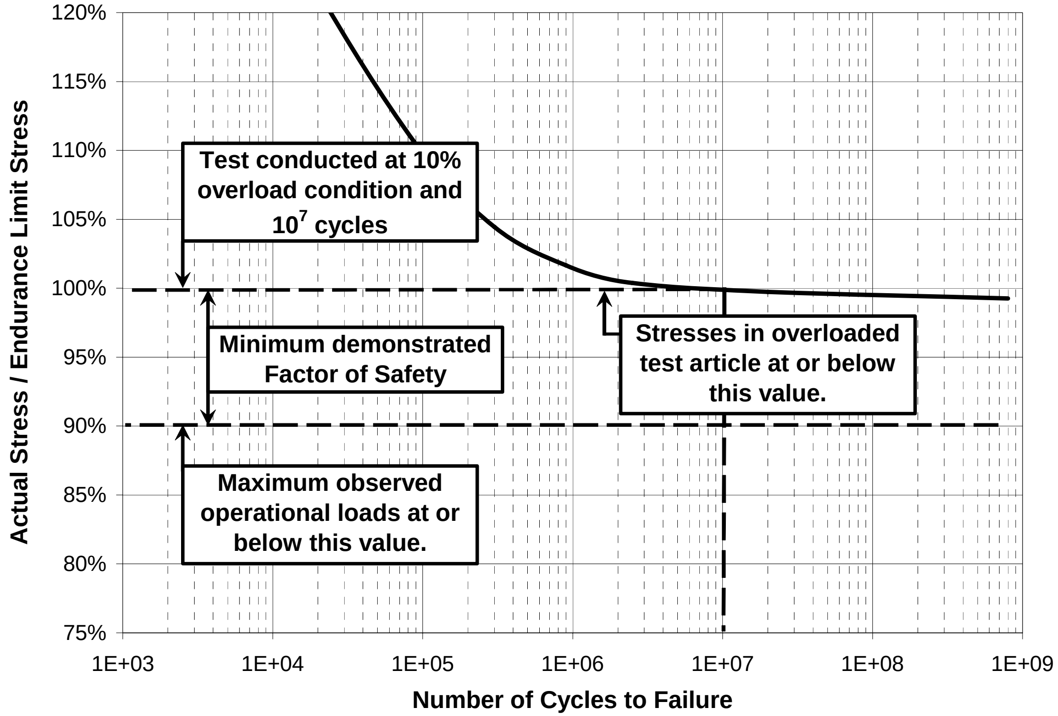
Crankshaft Major Change

- Challenge
  - Implement material change as product improvement
  - Demonstrate Durability and Endurance
    - Improved Demonstration of Long Term Durability
    - Demonstrate Meaningful Factor of Safety
      - Overload Operating Conditions
      - Inadvertent Manufacturing Deviations
  - Economical / Timely Test Program



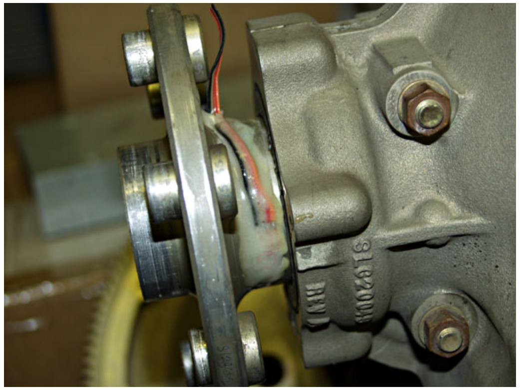
Improved Fatigue Testing Approach

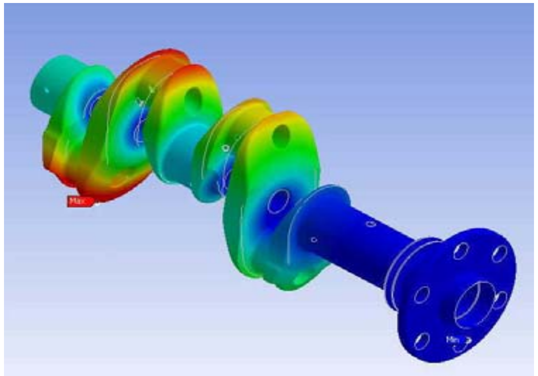
- Method
  - Utilize asymptotic nature of S-n curve
    - Small stress overload yields significant FS
    - Overloaded test condition demonstrates “essentially infinite life”
    - Factor of Safety defined by stress overload
    - Lack of failure defines as “minimum” Factor of Safety



Stress vs. Operating Load

- Test conditions must provide intended stress overload
  - Crankshaft stress not always linear with power
  - Combination of forced and resonant vibration may yield higher stresses at lower power loads
  - Evaluate
    - Direct Measurement
      - Sometimes difficult to accomplish
    - Finite Element Analysis
      - Must be used together with test data
      - Best when used as comparative tool



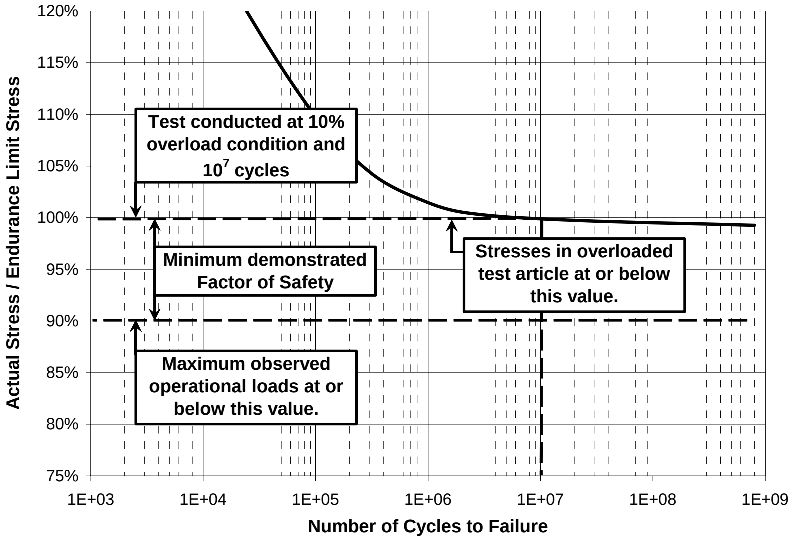


Crankshaft Stress Evaluation

- Bending Fatigue
  - Stress proportional to engine power
    - Inertia varies directly with speed
    - Cylinder pressure varies directly with torque
- Torsional Fatigue
  - Resonant vibration influential
  - Frequency varies with speed/power
  - Result = change in load phasing
    - Direct (combustion, inertia, etc)
    - Mass-elastic response of system
  - 10% stress increase ~ 20% load increase

Results

- Bending Fatigue Durability
  - 10^7 cycles
  - 10% overload = 10% overstress at Max Rated Speed
  - Complies with 14CFR Part 33 §33.43(b), "Vibration Test"
- Torsional Fatigue Durability
  - 10^7 cycles
  - 10% overstress
    - 20% overload
    - 110% Max Rated Speed
  - Complies with 14CFR Part 33 §33.43(b), "Vibration Test"
- 150^+ hours @ 110^+% Speed/Load
  - Exceeds 14CFR Part 33 §33.49, "Endurance Test"
- Demonstrated FS >> AC 33.19-1 Requires



Summary

- Alternate Crankshaft Alloy Implemented
  - More commercially available
  - Improved Nitriding Capability
  - Improved Process Safety Factor
  - Improved Safety for Flying Public

- Implementation Process and Testing
  - Complies with Relevant Regulations
  - Supports Intent of Guidance Materials
  - Demonstrates Minimum Factor of Safety
    - was not feasible under previous, conventional test methods

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Thank You !